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Recommendations for nutrient management plans in a semi-arid environment

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ABSTRACT

A nutrient management plan (NMP) field experiment was conducted to investigate the fate of nitrogen (N), phosphorus (P), potassium (K) and salts in a semi-arid environment (San Jacinto, CA). Our mechanistic approach to study NMP performance was based on comprehensive measurements of water and N mass balance in the root zone. A cereal crop rotation (wheat-rye hybrid to sorghum, *Triticum aestivum* L.–*Secale cereale* L. to *Sorghum bicolor* L. Moench) that does not fix atmospheric N was employed during 2007, whereas a legume crop (alfalfa, *Medicago sativa* L.) that forms nodules to fix N was used in 2008. Blending (2007 and 2008) and cyclic (2007) dairy wastewater (DWW) application strategies (no statistical difference in 2007) were implemented to meet crop water and N uptake. The high content of salts in DWW and accurate application of water to meet evapotranspiration (*ET*) yielded salt accumulation in the root zone. Leaching these salts after the fallow period resulted in the flushing of nitrate that had accumulated in the root zone due to continuous mineralization of soil organic N. This observation suggested that a conservative NMP should account for mineralization of organic N by (i) leaching salts following harvests rather than prior to planting and (ii) maintaining soils with low values of organic N. For the wheat-rye hybrid–sorghum rotation, losses of nitrate below the root zone were minimal and the soil organic N reservoir and P were depleted over time by applying only a fraction of the plant N uptake with DWW (28–48%) and using DWW that was treated to reduce the fraction of organic N (3–10%), whereas K accumulated similar to other salts. Conversely, with alfalfa approximately 15% of the applied N was leached below the root zone and the soil organic N increased during the growing season. These observations were attributed to fixation of atmospheric N, increased root density, and applying a higher fraction of plant N uptake with DWW (76%). Collectively, our results indicate that NMPs should accurately account for water and nutrient mass balances, and salt accumulation to be protective of the environment.

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1. Introduction

Concentrated animal feeding operations (CAFOs) have been identified as potential point sources of pollutants to surface water and groundwater (USEPA, 2003). Currently, the USEPA requires that application of CAFO wastewater to agricultural lands follows approved nutrient management plans (NMPs). NMPs are designed to meet the water and nutrient needs of crops, while minimizing the loss of nutrients to surface water and groundwater (USEPA, 2003). However, researchers with the USEPA have observed significant migration of pollutants (e.g., nitrate) towards surface water and groundwater bodies at NMP sites (personal communication). These observations suggest that implementing a NMP based on current agronomic practices may not always protect the environment.

Wastewater from concentrated animal feeding operations contains high levels of plant nutrients, organic compounds, and inorganic salts (Chang and Entz, 1996; Hao and Chang, 2003; Longhurst et al., 2000; Bradford et al., 2008). Excess amounts of these constituents can adversely impact soil and water quality (Jokela, 1992; Chang and Entz, 1996; Craun and Calderon, 1996; USEPA, 1997, 2000; Bond, 1998; Houlbrooke et al., 2004). On the other hand, CAFO wastewater and manure may be valuable fertilizers and soil amendments that improve soil physical conditions for plant growth (Jokela, 1992; Kapkiyai et al., 1999; Houlbrooke et al., 2004), reduce energy required for tillage (Sommerfeldt and Chang, 1985, 1987), and increase the organic matter content of soil (Sommerfeldt et al., 1988; Stenger et al., 2001). In semi-arid and arid environments the reuse of CAFO wastewater for irrigation reduces demand for high quality water, a scarce resource (Pimentel et al., 2004).

NMPs involve mass balance considerations for a limiting nutrient for plant growth or a nutrient that is the primary environmental concern. Nitrogen (N) and phosphorus (P) are two of the most limiting nutrients affecting plant production in semi-arid environments. Plant uptake of N is typically higher than P (Russell, 1973). Hence, NMPs based on P will use smaller quantities of CAFO wastewater

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than a NMP based on N, and will also require additional N fertilizer. Conversely, NMPs based on N will tend to over apply P (Houlbrooke et al., 2004). Semi-arid soils are characterized by a higher pH and abundant calcium and magnesium that result in solid phase P precipitates (Holford, 1997). Furthermore, potential transport of P in soils was found to decrease in the presence of manure (Brock et al., 2007). All of these considerations indicate that it is reasonable to develop NMPs based on N for mineral soils in semi-arid environments.

NMPs for CAFO wastewater application that are protective of groundwater should accurately quantify water and nutrient balances. Information is needed on the actual crop evapotranspiration (*ET*), the amount of irrigation and/or precipitation, the uniformity of the applied irrigation, the soil water status in and below the root zone, and the soil hydraulic properties in order to conduct a thorough water balance. In addition, a nutrient balance requires information on all relevant sources and sinks. Potential sources of N include: CAFO wastewater, fertilizer, the mineralization of soil organic N, and fixation of atmospheric N by leguminous crops. Dominant N sinks include: plant uptake of inorganic N, drainage, and volatilization. Many of these nutrient sources and sinks are dependent on complex biogeochemical transformations (Bradford et al., 2008). Neglecting temporal variations in nutrient sources and sinks may result in over or under applications of water, nutrients, or both during different periods of the growing season. Experimental determination all relevant water and nutrient balance information for NMPs throughout the growing season is therefore a challenging task.

Most previous NMP studies have pragmatically been designed from an agronomic viewpoint (Hubbard et al., 1987; Adeli et al., 2003; McLaughlin et al., 2004; Woodard et al., 2002), and have incompletely determined or neglected information for water and nutrient balances. Rates of crop nutrient recovery have been found to reflect quantities left in soil in and below the root zone (Adeli et al., 2003). Growth and nutrient uptake requirements of warm-season grasses differed between annual and perennial species, and crop growth and nutrient uptake rates were influenced by seasonal drought (McLaughlin et al., 2004). Estimates of total biomass, crop and soil nutrient concentrations in contrasting crop rotation systems (annual forages compared to perennial grasses) indicated time between harvests and planting, rate of ammonia volatilization, and temperature-related rates of mineralization of organic N all influenced plant N extraction rates (Woodard et al., 2002) and nitrate leaching to groundwater. Reductions in groundwater nitrate levels are also influenced by net groundwater recharge rates, soil permeability, and depth to water table (Harter et al., 2001). Efficient implementation of a NMP has been reported to be more difficult when there is a high ratio of organic to inorganic N, because organic N forms are not available for plant uptake until after mineralization into inorganic forms (Cameron et al., 2002; Crohn, 2006).

Benefits of using CAFO wastewater for fertilizer may be partially offset by accumulation of salts in the root zone. Plant uptake of salt is typically very minimal (Russell, 1973) and concentration of salts in the root zone by *ET* is known to deteriorate plant growth and yield (Maas and Hoffman, 1977). Two conventional practices to minimize the adverse effects of salt accumulation are: (i) growing salt tolerant crops (Tanji and Kielen, 2002), and (ii) periodic leaching of salts below the root zone (Bond, 1998). Leaching of salts, however, may also transport nutrients below the root zone toward groundwater resources. The groundwater contamination potential by leached nutrients will depend on the nutrient species and concentration, leaching fraction, depth to groundwater, and preferential water flow that can accelerate the migration rate of nutrients that bypass the soil matrix.

The above literature indicates that potential problems with NMP implementation include: (i) inaccurate quantification of water and nutrient mass balances due to inadequate information on soil properties, climatic data, wastewater constituents or crop water and nutrient uptake rates; (ii) inherent spatial and temporal variability in NMP properties; and (iii) NMP management constraints, such as water and wastewater application amounts and the timing. The objective of this study is to measure the fate of nitrogen, phosphorus, potassium and salts from land application of dairy wastewater under a well-designed and implemented NMP in a semi-arid environment. We also present key management practices that minimize the potential leaching of nutrients and salts toward groundwater.

2. Materials and methods

Traditional NMP studies have been conducted from an agronomic perspective to determine the impact of specific NMP factors on a given field. The statistical design for such experiments include blocks and random repetitions because the spatial variability of the field and application systems is typically unknown. In contrast, our experiment was a process-based (mechanistic) study of flow and transport processes under NMP conditions. Accurate implementation of a process-based NMP requires the determination of water, salt and nutrient mass balances in the root zone, and the ability to quantify flow and transport processes. To collect this type of information requires the use of measurement tools such as weighing lysimeters, weather station, tensiometers and solution samplers with depth, and irrigation systems with a high level of uniformity and precision. The traditional agronomic design cannot achieve such high precision in measuring and implementing a NMP on each repetition due to economic constraints, and this further increases the variability of traditional NMP studies. Below we highlight the design of our process-based NMP that was needed to overcome the limitations of the traditional agronomic approach.

2.1. Field

Our field site was located in San Jacinto, CA (33°50′22″North, 117°00′46″West) and was chosen to be in a relatively homogenous part of the field in order to minimize variability in soil hydraulic properties. This objective was achieved by acquiring preliminary information on the field soil spatial variability using a remote electromagnetic induction system (Segal et al., 2008). This procedure eliminated the need of repetitions scattered across the field such as in traditional agronomic NMP studies, and allowed us to focus on within plot variability. The experiment site was also chosen to have no recent history of CAFO wastewater application. The field was cultivated only during winter (wheat-rye hybrid, Triticale, TRICAL® Resource Seeds, Inc.) and manure was applied twice (the last manure application was 3 years prior to this experiment) during the last 10 years prior to this experiment.

The experimental site consists of two 6 m × 6 m plots (Fig. 1), more detailed description of the site is given in Segal et al. (2008, 2009). Within plot variability was overcome by taking multiple measurements over depth at several locations within the plots. Briefly, one culvert pipe was installed at each corner of both plots (eight pipes total). Each pipe was instrumented with six tensiometers and six soil solution samplers installed over depth at approximately 30 cm intervals, which were installed 90 cm horizontally from the culvert pipe into the undisturbed soil profile. The staggered configuration of the sensors (represented by the arc in Fig. 1), was selected to maximize the area of the profile that was sampled. Each plot was also equipped with five neutron probe (503-DRHYDROPROBE®, CPN, Martinez, CA) access tubes for measuring the water content with depth.

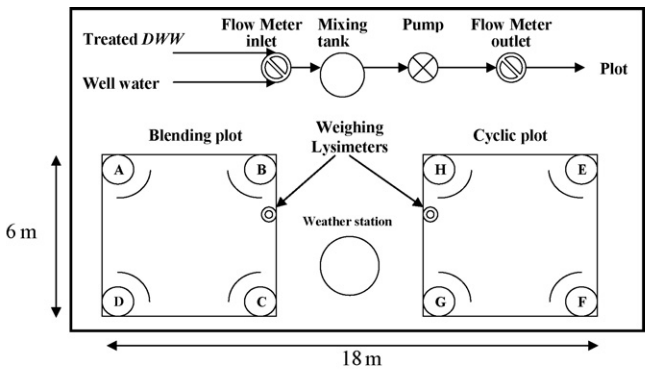

Fig. 1. Schematic of the field site. Squares represent two six-by-six meter plots. Circles with letters (A–H) are 220 cm in length vertical culvert pipes installed with tensiometers and solution samplers. Arcs represent the area of water potential and soil solution sampling. The controlled mixing and application system is illustrated at the top of the figure.

An intensive study on water flow and soil hydraulic properties was conducted on the two plots at our experimental site (Segal et al., 2008) and no significant difference was found between the plots. The soil texture of the root zone (0–65 cm) was a sandy loam (Grangeville fine sandy loam, a coarse-loamy, mixed, superactive, thermic fluvaquentic haploxeroll) with average contents of 55% sand, 40% silt and 5% clay. The average bulk density was 1.35 g cm^{-3} and the saturated and residual water contents were 0.43 and 0.03, respectively. The average saturated hydraulic conductivity was 2.35 cm h^{-1}, the longitudinal dispersivity was 0.56 cm, the immobile water content was 0.0978, and the mass transfer coefficient between mobile and immobile regions was 0.0035 h^{-1} (Segal et al., 2008, 2009).

Raw DWW was treated prior to land application with a stationary inclined screen separator (Zhang and Westerman, 1997), a sedimentation tank (Sukias et al., 2001), and a sand filter (Rodgers et al., 2005) packed with crushed silica (0.45–0.5 mm in diameter, AGF, Netafim, Fresno, CA). In contrast to traditional agronomic designs, our process-based NMP minimized variability through uniform application of water and nutrient with a high level of precision. Specifically, well water and/or DWW were uniformly applied to each plot using a pump and nine emitters (R184CT, Raindrip, Fresno, CA) in 3 m spacing. The water application rates varied between 0.6 and 0.95 cm h^{-1} (25–40% of the soil saturated hydraulic conductivity) with a Christiansen uniformity coefficient of 94% under low wind conditions. The water and wastewater application system consisted of a mixing tank, a controller, solenoid valves, pumps and two electrical water meters with a resolution of 3.78L ± 1.5% (JSJ075, Carlon meter, Grand Haven, MI) to achieve desired blending ratios for treated DWW and well water (Fig. 1). Dairy wastewater was applied using cyclic and blending strategies. The blending strategy employed a selected mixture of treated DWW and well water to meet the needs of the crop for N and water. Conversely, the cyclic strategy applied separate irrigations of treated DWW and well water to meet the crop needs for N and water.

A NMP was implemented on winter and summer crops during 2007, and a perennial crop in 2008. Wheat-rye hybrid (Triticale, TRICAL® Resource Seeds, Inc.) served as the 2007 winter crop and was planted on February 10th, seedlings emerged and established a full stand on February 25th, and the crop was harvested on May 8th. The 2007 summer crop was NK 300 hybrid forage sorghum (Syngenta Global) and was planted on May 30th, seedlings emerged and established a full stand on June 5th, and the crop was harvested on August 13th. The 2008 perennial crop was alfalfa (Grandslam cv. Western Farm Service, CA). Alfalfa is an important crop for the dairy industry due to its high yield, feeding value and efficiency in N removal. Alfalfa has three major differences relative to the crops used in 2007, namely: (i) it is a perennial crop with multi-cuts, (ii) it has a deeper root system, and (iii) it may assimilate N from the atmosphere through nodules (symbiotic nitrogen fixation). Alfalfa was planted on the blending field plot at agronomical rate of 2.75 kg ha^{-1} on April 1st, emerged on April 10th, and established full cover 30 days later. Five consecutive growing cycles (five cuttings with harvest interval between 37 to 45 days) were achieved during 2008. The NMP was implemented by dividing the growing season into multi-cut segments that represent the growing cycle. Each growing cycle was consider a separate period with a new initial condition. The first growing cycle started on May 10th and lasted until June 17th. However, extensive weed growth interfered with the normal development of the alfalfa during this period. Therefore, the plot was treated with herbicide (Pursuit, BASF, NC) at the rate of 150 mL ha^{-1} on June 25th. A fallow season (time between harvest and planting that is associated with minimal *ET* and nutrient uptake) occurred between successive growing seasons for the crops described above.

Blumenthal and Russelle (1996) reported that atmospheric N fixation through nodules will be less active during periods of high inorganic N in the soil. The alfalfa NMP therefore attempted to maintain high N concentrations in the root zone during the growing season in order to minimize the amount of N fixation and to maximize the amount of DWW addition. No DWW was applied between the last two alfalfa harvests in order to deplete the soil profile of plant available N.

2.2. Water and nitrogen mass balances in the root zone

Plot scale water balance information in the root zone over a given time interval was used to determine the amount of applied irrigation water, I (ML^{-3} ΔT^{-1}) to meet crop ET (ML^{-3} ΔT^{-1}) at the end of this interval as

$$I = ET + D + \Delta W - P_w \quad (1)$$

where D (ML^{-3} ΔT^{-1}) is water loss due to drainage, P_w (ML^{-3} ΔT^{-1}) is the water input due to precipitation, and ΔW (ML^{-3} ΔT^{-1}) is the change in soil water storage (final–initial).

Water balance parameters in Eq. (1) were measured as described below. Potential ET (ET_p), with a resolution of 0.1 mm, was estimated using data from a weather station (Penman, 1948) located between the plots. Temperature, relative humidity, solar radiation, wind speed and rain were recorded every 15 min. Actual ET (ET_{actual}) was estimated from weighing lysimeters, 20 cm in diameter and 100 cm length, installed at the perimeter of each plot (Fig. 1). The top of the lysimeter was at the soil surface connected to a load cell that measured the total weight continuously (resolution of 50 g). A suction cup (filter paper; MF-0.45 μm, Millipore, Billerica, MA) was connected to the bottom of the lysimeter, where vacuum can be applied to collect the drainage. The crop coefficient (K_c) was calculated as the ratio of ET_{actual} to ET_p during a given time period. Alternatively, K_c can also be estimated from literature values (Allen et al., 1998). The value of P_w (resolution of 0.25 mm) was measured using a rain gauge (CS700, Campbell scientific, Logan, UT). The values of D and ΔW were determined from neutron probe and tensiometer readings in the soil profile and measured soil hydraulic properties. The value of I was verified from flow meter readings.

In this study the following inorganic and organic N mass balance equations for the root zone were employed:

$$N^I_{application} + E_{OI} = N^I_{plant} + N^I_{drainage} + N^I_{atmosphere} + \Delta N^I_{soil} \quad (2)$$

$$N^O_{application} = \Delta N^O_{soil} + E_{OI} \quad (3)$$

Table 1
Ammonia volatilization from the sprinkler irrigation system and soil surface.

Late winter DAE[a]	Application strategy	$N\text{-}NH_4$ in irrigation water $mg{\cdot}L^{-1}$	Volatilization loss (%)	Potential ET^b ($mm\,h^{-1}$)
$N\text{-}NH_3$ volatilization from sprinkler irrigation system				
35	Blending	11.1	15	0.446
35	Cyclic	39.45	9	0.142
57	Blending	92.57	32	0.68
57	Cyclic	157	22	0.24
Late winter DAE	Application strategy	$N\text{-}NH_4$ in irrigation water ($mg\,m^{-2}$)	$N\text{-}NH_3$ volatilization ($mg\,m^{-2}$)	Volatilization loss (%)
$N\text{-}NH_3$ volatilization from soil surface				
29–36	Cyclic	2407.82	1.614	6.7×10^{-6}

[a] DAE is day after emergence.
[b] *ET* is evapotranspiration.

where $N^I_{application}$ is the inorganic N applied to the soil surface ($ML^{-3}\,\Delta T^{-1}$), E_{OI} ($ML^{-3}\,\Delta T^{-1}$) is the amount of N converted from/to organic to/from inorganic forms, N^I_{plant} ($ML^{-3}\,\Delta T^{-1}$) is the inorganic N uptake by the plant, $N^I_{drainage}$ ($ML^{-3}\,\Delta T^{-1}$) is the inorganic N drained below the root zone, $N^I_{atmosphere}$ ($ML^{-3}\,\Delta T^{-1}$) is the inorganic N lost to the atmosphere, ΔN^I_{soil} is the difference in inorganic N storage in the root zone (final–initial), $N^O_{application}$ ($ML^{-3}\,\Delta T^{-1}$) is the organic N applied to the soil surface and ΔN^O_{soil} ($ML^{-3}\,\Delta T^{-1}$) is the difference in organic N storage in the root zone (final–initial). The total N mass balance is equal to the sum of Eqs. (2) and (3). Eq. (3) assumes that losses of organic N are only due to mineralization (volatilization and drainage of organic N are assumed to be negligible).

The N mass balance was calculated over the upper 30 cm for the wheat-rye, 60 cm for the sorghum and 90 cm for the alfalfa, where roots are most active in water and nutrient uptake under irrigated conditions (Kätterer et al., 1993; Merrill and Rawlins, 1979; Abdul-Jabbar et al., 1982). Nitrogen balance parameters were quantified as described below. Total N and C in the solid phase of the DWW, soil, and plant tissues were measured using the combustion method (Flash EA 1112, Thermo-Finnigan, Waltham, MA). Measurement of nitrogen from ammonium ($N\text{-}NH_4$) (Keeney and Nelson, 1982) and nitrogen from combined nitrite and nitrate ($N\text{-}(NO_2 + NO_3)$) concentrations in soil solution and DWW were performed using a colorimetric system (O.I. Analytical, Flow Solution IV, College Station, TX) after filtering the sample through a 0.22 μm filter. Values of $N^I_{application}$ and $N^O_{application}$ were directly measured in the DWW before each application. The value of ΔN^I_{soil} was determined from sequential measurements of soil inorganic N concentrations in the root zone before DWW application events. The value of $N^I_{drainage}$ was determined from measured inorganic N concentrations in soil solution below the root zone and from information about the water fluxes.

$N^I_{atmosphere}$ accounts for volatilization of ammonia (NH_3) during application and from the soil surface. We assumed denitrification was negligible under the low nitrate and unsaturated conditions of the root zone (Luo et al., 1999). The loss of NH_3 during irrigation was measured using the concentration ratio of $N\text{-}NH_4$ in the irrigation water at the emitter outlet and at the soil surface. Volatilization of NH_3 from the soil surface was measured following DWW application for a period of 1 week during the 2007 winter crop season using a standard chamber and acid-trap technique to capture NH_3 emissions (Black et al., 1985). The loss of $N\text{-}NH_4$ during irrigation and the ET_p are presented for two application events in Table 1. The $N\text{-}NH_4$ losses during irrigation varied between 9 and 32%, and higher rates were associated with higher $N\text{-}NH_4$ concentrations in the irrigation water and higher ET_p. The atmospheric loss of $N\text{-}NH_4$ during irrigation was measured and taken into account in the N balance before each application. The loss of $N\text{-}NH_4$ from the soil after irrigation was measured to be three orders of magnitude smaller than the $N\text{-}NH_4$ loss to the atmosphere during irrigation (Table 1). These findings are consistent with other data presented in the literature (Cameron et al., 1995, 2002; Sharpe and Harper, 1997; Hawke and Summers, 2006).

N^I_{plant} was determined from measurements of dry phytomass and its N content. Before each water application, a 1 m long row of plants of the wheat-rye and sorghum (0.2–0.4 m^2) or 0.3 by 0.3 m of the alfalfa was collected for N analysis from the middle of the plot, where minimal effects from the measuring devices are expected. Since the root system was not removed during the harvesting, it was not considered as an N sink.

For wheat-rye hybrid and sorghum during 2007 the value of E_{OI} accounts for the net exchange due to mineralization. In contrast, for alfalfa (a legume) during 2008 the value of E_{OI} also accounts for N fixation from the atmosphere. The value of E_{OI} was determined from Eq. (2), while all other parameters were measured, and this information was used in conjunction with Eq. (3) to determine the changes in N^O_{soil} using measured average values of the initial N^O_{soil} at the field site. The exchange rate was subsequently calculated as E_{OI} divided by the initial N^O_{soil} for a given time period. Final total N (dominated by N^O_{soil}) and its spatial variability in the plots were measured on March, 2008. Ten soil cores, 30 cm long by 1.25 cm in diameter, were sampled from each plot in random locations. Three samples were taken from each core at depths of 5, 15 and 25 cm (total of 30 samples, 10 at each of these depths). Due to the small soil volume used in the combustion method, each sample was divided into three subsamples (total of 90 subsamples) that were analyzed for their total N and C content.

In practice, $N^I_{application}$ was calculated from Eq. (2) to meet the projected N^I_{plant} and E_{OI} during the subsequent time interval. The projected plant uptake for each time interval was determined from potential N uptake curves for crops under optimum growth conditions (Bélanger and Richards, 2000; Gibson et al., 2007; Rahman et al., 2001), and the projected mineralization rate was estimated from literature values (Stenger et al., 2001) or from the previous time step. The blending ratio before each application was determined by matching simultaneously $I_{application}$ and $N^I_{application}$, where $I_{application} = I_{DWW} + I_{well}$ and $N^I_{application} = N^I_{well} I_{well} + N^I_{DWW} I_{DWW}$ and the subscripts *DWW* and *well* denote the water source.

Suspended sediment concentration (SSC) of the DWW was measured by centrifuging a known volume at 2040 times gravity for 20 min, decanting the liquid phase and measuring the remaining solid after drying at 60 °C for 48 h (ASTM D 3977-97 – Method A). The TDS was assumed to be correlated to the EC ($1\,dS\,m^{-1} = 640\,mg\,L^{-1}$) and was measured with an EC meter (M33.1, Agricultural electronics, Montclair, CA). The concentrations of plant available K (Olsen bicarbonate method) and P (ammonium acetate method) in the soil profile were determined at the beginning and the end of the 2007 growing season, whereas salt

Table 2
Potential and actual evapotranspiration (*ET*), crop coefficient, rainfall and water application during the growing season of wheat-rye hybrid during winter 2007 (A) and sorghum during summer 2007 (B), DAE is day after emergence.

DAE	potential *ET* mm	Crop coefficient and leaching factor[a]	Actual *ET* mm	Rainfall mm	Water application mm
A					
15–29	100.2	0.5	50.1	7.25	42.9
30–36	30.1	0.5	15.05	0.00	15.0
37–50	84.4	0.9	75.96	4.25	71.7
51–58	36.7	1.1	40.37	4.00	36.3
59–65	39.8	1.2	47.76	13.25	34.6
66–72	40.1	1.2	48.12	0.00	48.0
B					
5–28	258.6	0.5	129.3	0.00	135.1
29–35	86.7	0.75	65.02	0.00	62.4
36–44	94.0	0.9	84.6	0.00	90.5
45–49	47.1	1.0	47.1	0.00	48.5
50–58	86.0	1.0	86.0	0.00	86.6
59–62	33.5	1.05	35.17	0.00	35.3
63–70	59.8	1.1	65.78	0.00	66.6

[a] Crop coefficient was measured based on water mass balance in the root zone by using weighing lysimeters. The leaching factor was 0.2 during the first 30 days and 0.1 through the rest of the growing season.

concentrations (EC and TDS) in the root zone were measured before each irrigation event.

The *T*-statistic (*T*-test) was used to evaluate significant differences ($P < 0.05$) between cyclic and blending application strategies during 2007 (Sigmaplot 11, Systat Software Inc., CA).

3. Results and discussion

Results from wheat-rye hybrid (winter 2007) and sorghum (summer 2007) data are discussed below in sections entitled *Management considerations for salinity*, *Management considerations for organic nitrogen*, and *Plant available* N, P *and* K. These two cereal crops do not form nodules to fix atmospheric N, and E_{OI} therefore reflects exchange due to mineralization. In contrast, alfalfa (summer 2008) is a legume that forms nodules and may fix atmospheric N. The additional N source from fixation poses additional challenges for efficient NMP implementation that is discussed below in a separate section entitled *Nitrogen fixation—alfalfa 2008*.

3.1. Management considerations for salinity

Water balance information for 2007 winter (A) and summer (B) growing seasons are presented in Table 2. Rainfall occurred during winter (total of 28.75 mm) but was absent during summer. The value of ET_p was lower during winter than during summer. The final water application amounts were adjusted to include a leaching factor of 0.2 for the first 30 days and 0.1 for later times in order to leach excess salts from the root zone and to minimize downward migration of NO_3^-. A system malfunction, however, delivered an extra 55.4 mm of well water to the cyclic plot on day 58 of the summer growing season. The total drainage flux (average of the blending and cyclic strategies) below the root zone was 23.9 and 56.4 mm throughout the winter and summer growing seasons, respectively.

Fig. 2 presents the absolute value of soil water pressure head (|*h*|) in the soil profile as a function of day after emergence (DAE) for the blending and cyclic strategies during the 2007 summer growing season. Changes in |*h*| were restricted only to the upper 60 cm of the soil profile due to the accurate water mass balance on both plots. In general, |*h*| followed the water application events: decreasing after irrigation and increasing with time between irrigations. Fig. 2 shows that aerobic conditions were maintained during the majority of the season. The soil water pressure head below the root zone (i.e., <−90 cm) was generally steady throughout the growing season. The system malfunction on the cyclic plot at day 58, however, caused a decrease in |*h*| below the root zone (<−60 cm).

The increase in the EC of soil solution (EC_w) of the root zone (−30 and −60 cm) over time due to the use of irrigation water with high TDS, a low leaching factor, and concentration of salts by *ET* is presented in Fig. 3. The EC_w of the root zone increased from 1 to 3 dS m^{-1} for the blending strategy and from 1 to 2.5 dS m^{-1} for the cyclic strategy (no significant difference in the level of $P < 0.05$ were found between the final values of EC_w of each treatment). The extra water application on the cyclic plot produced greater leaching and hence a lower final value of EC_w. Only minor changes in the electrical conductivity of the soil solution (EC_w) were detected below the root zone during the growing seasons (data is not presented), due to the low leaching factor that was implemented at these sites.

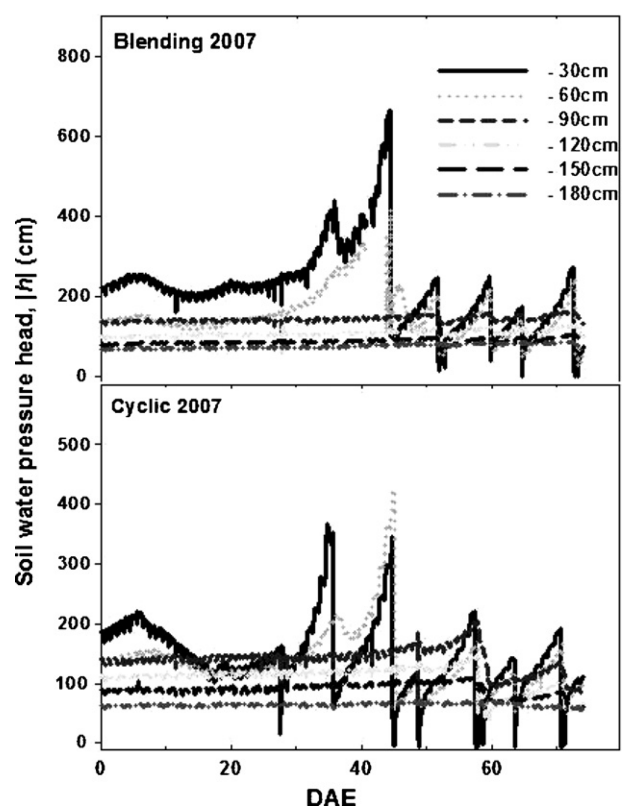

Fig. 2. The absolute value of the soil water pressure head (|*h*|) in the soil profile as a function of day after emergence (DAE) for the cyclic and blending water application strategies during the sorghum 2007 growing season.

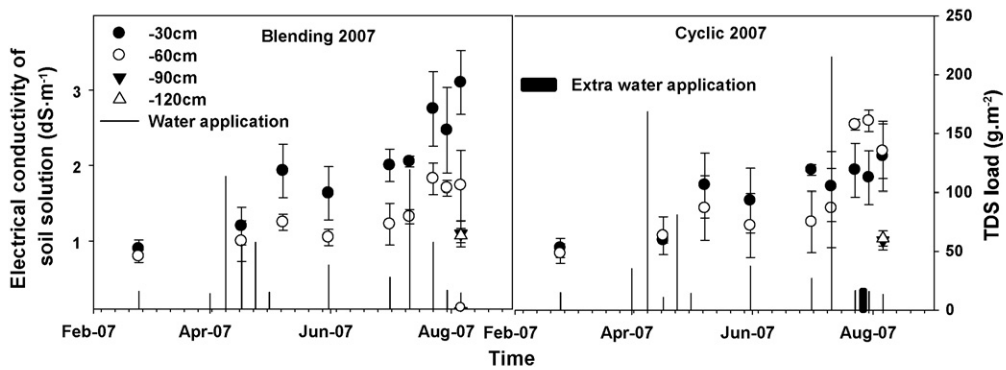

Fig. 3. Electrical conductivity of the soil solution (EC_w) over depth and total dissolve solids (TDS) load during 2007 for the blending and cyclic water application strategies. Error bars represent measured standard deviations.

The measured values represent the salt load under a conservative NMP approach that applied only a fraction of the total N that was required by the plant with DWW. If 100% of the plant N had been applied by DWW, then the accompanied salts would increase the EC_w in the root zone to higher levels. High salt levels in the root zone may restrict plant growth, and accordingly water and nutrient uptake. If this reduction in *ET* is not considered at a NMP site, additional leaching and contaminant migration will occur. An optimum point likely exists between the benefits of nutrient application and the detrimental effects of salt accumulation on crop yield. This point is strongly dependent on the salt tolerance of the crop, suggesting that NMP should use only salt tolerant crops.

Minimizing the potential adverse effects of salts on plant growth is commonly achieved by leaching excess salts below the root zone. The timing of salt leaching may be a crucial management decision in NMPs because organic soil N continues to be converted to inorganic N forms (NH_4^+, NO_2^- and NO_3^-) during the fallow season. A pre-irrigation at the beginning of a new growing season, or seasonal rains during the fallow season may result in migration of inorganic N, especially NO_3^-, below the root zone towards groundwater (Feng et al., 2005; Woodard et al., 2002).

Fig. 4 demonstrates this scenario by presenting the concentrations of N-(NO_2 + NO_3) and N-NH_4 in the soil profile at the end (final – after harvesting) and beginning (initial – after seasonal rains and pre-irrigation) of consecutive growing seasons. The graphs of wheat-rye 2007/sorghum 2007 and the sorghum 2007/alfalfa 2008 fallow seasons show that the soil profile at both strategies was depleted from inorganic N at the beginning of the fallow seasons. Conversely, high concentrations of N-(NO_2 + NO_3) were found along the soil profiles at the end of the fallow seasons. No significant difference (P < 0.05) between strategies was found in the initial and final values of N-NH_4 and N-(NO_2 + NO_3) in the soil profile. A mass balance of the inorganic N in the profile revealed that 9.67 and 17.95 g of N m^{-2} was mineralized for the blending strategy and 3.40 and 19.5 g of N m^{-2} for the cyclic strategy during the wheat-rye 2007/sorghum 2007 and the sorghum 2007/alfalfa 2008 fallow

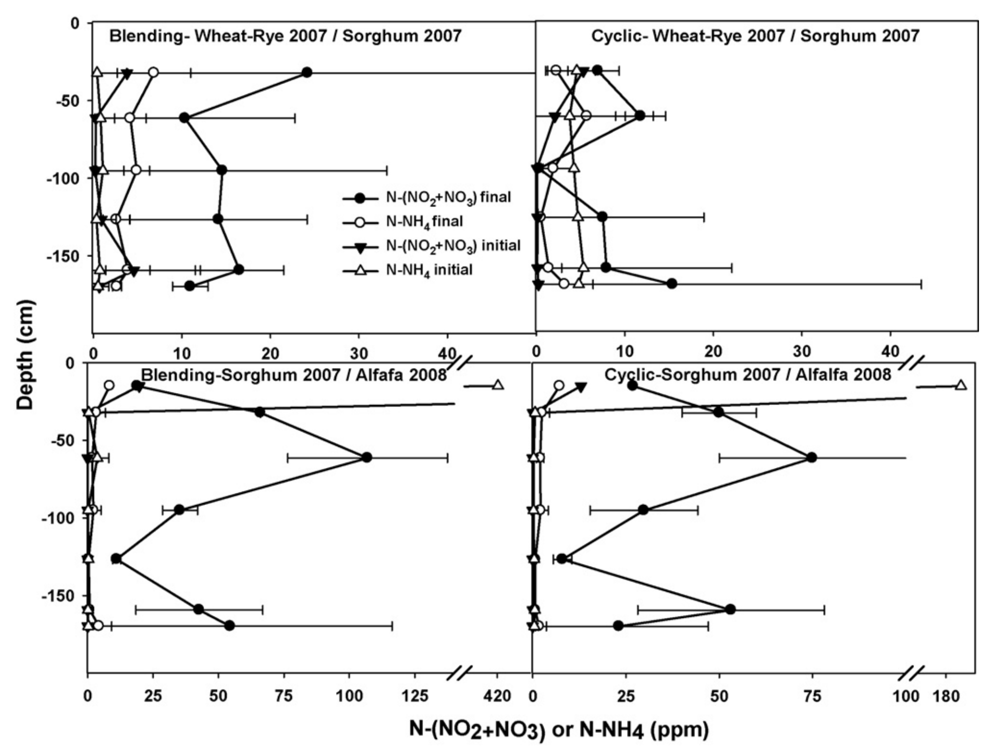

Fig. 4. Nitrogen from ammonium (N-NH_4) and nitrogen from combined nitrite and nitrate (N-(NO_2 + NO_3)) concentration in the soil profile at the end (initial fallow) and beginning (final fallow) of two consecutive growing seasons (wheat-rye 2007/sorghum 2007 and sorghum 2007/alfalfa 2008). Error bars represent measured standard deviations.

periods, respectively. These values are equivalent to mineralization rate of 2.37E−04 day^{-1} and 4.25E−04 day^{-1} for the blending strategy and 2.93E−04 day^{-1} and 4.72E−04 day^{-1} for the cyclic strategy. Leaching excess salts is therefore recommended right after harvesting, when the inorganic N, and especially NO_3^- levels are low in the root zone.

3.2. Management considerations for organic nitrogen

The determination of N^O_{soil} is hampered due to the inaccuracy of currently available methodologies (i.e., Kjeldahl and Combustion) and the inherent spatial variability of soils and water application systems (Strong et al., 1999; Stenger et al., 2001; Valenzuela-Solano and Crohn, 2006; Watts et al., 2007). Significant variability in N^O_{soil} was observed at the beginning of the 2008 winter growing season.

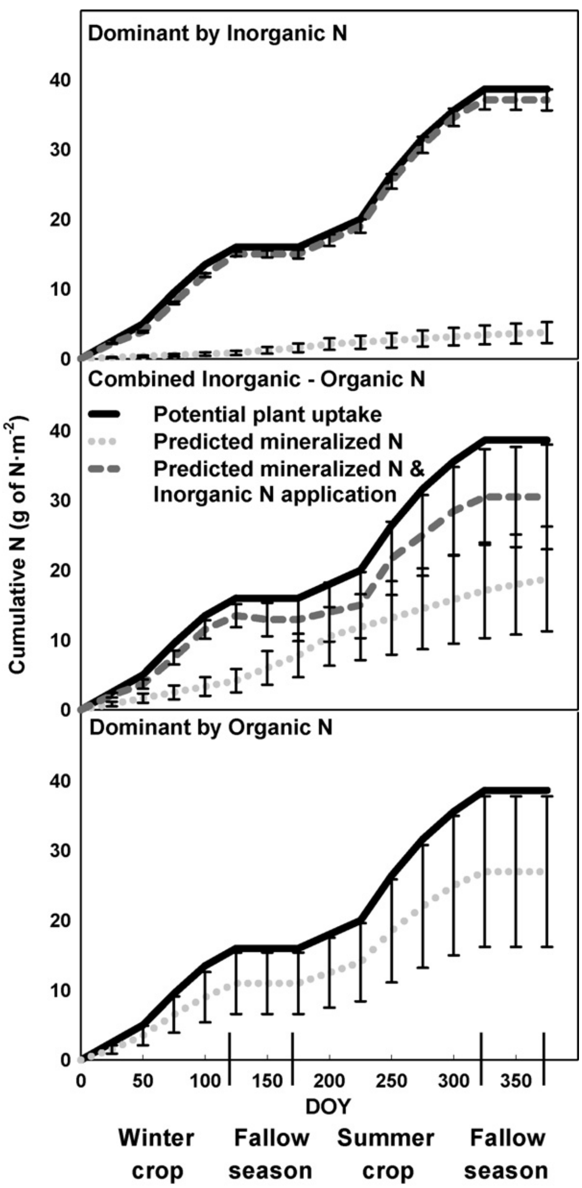

Fig. 5. Three conceptual approaches for nitrogen NMPs based on low (top figure: 333 g of N m^{-2}), intermediate (middle figure: 1666 g of N m^{-2}), and high (lower figure 3333 g of N m^{-2}) soil organic N reservoirs. Cumulative amounts of potential plant N uptake (16 and 22 g of N m^{-2} for winter and summer crops), predicted mineralized N, and the sum of mineralized N and applied inorganic N are presented as a function of the day of the year (DOY). Mineralization rates were 2E−04 and 3E−04 day^{-1} for winter and summer seasons. The error bars reflect the assumed variance (40%) in the mineralization rate.

The average total N (dominated by organic N) was 0.051% for the blending and 0.058% for the cyclic strategies, yet the values varied between 0.03 and 0.12%. This corresponds to total N levels of 121–486 g of N m^{-2} for the upper 30 cm. The calculated coefficient of variance for the combustion method was 6.95% and from the spatial variability was 19.5%. Hence, when the N^O_{soil} reservoir plays a dominant role in NMP management, the high uncertainty may lead to an inaccurate application of N. Furthermore, Fig. 4 suggests that a large N^O_{soil} reservoir can maximize the potential migration of NO_3^- below the root zone at the end of the fallow season.

Fig. 5 shows the effect of the high uncertainty and amount of N^O_{soil} on NMP implementation (in the absence of N fixation); by presenting three conceptual scenarios representing different ratios of inorganic to organic N sources in the root zone. The values of N^O_{soil} were assumed to be 333, 1666, and 3333 g of N m^{-2} in the top, middle, and lower figures. Cumulative amounts of potential N^I_{plant}, E_{OI}, and the sum of E_{OI} and $N^I_{application}$ as a function of day of the year (DOY) are presented for each N^O_{soil} level. The year is divided into two growing seasons (winter and summer) and two fallow periods (fall and spring). For winter and summer crops the cumulative amounts of potential N^I_{plant} were assumed to be 16 and 22 g of N m^{-2} and mineralization rates were assumed to be 2E−04 and 3E−04 day^{-1}, respectively. The error bars reflect the assumed variance (40%) in the mineralization rate. Differences in the predicted cumulative amounts of E_{OI} are due to differences in the initial organic reservoir. $N^I_{application}$ is determined from the difference between potential N^I_{plant} and E_{OI}, while considering the uncertainty.

For the case of a low N^O_{soil} reservoir, matching between potential N^I_{plant} and $N^I_{application}$ is practical with low deviations due to the minor amounts of N^O_{soil} and $N^O_{application}$. This well-controlled NMP condition is similar to fertigation. The second scenario, intermediate N^O_{soil} reservoir, is representative of our field study during 2007 and requires the consideration of E_{OI}, N^I_{soil} and $N^I_{application}$. This second scenario will under apply N^I_{plant} when uncertainty in the mineralization rate is considered and the N^O_{soil} reservoir will deplete over time and shift the system to the well-controlled NMP condition shown in the upper graph. In the third scenario, the entire N^I_{plant} is dependent on the N^O_{soil} pool and mineralization rates. When considering the high uncertainty in E_{OI}, significant under application of N is likely with corresponding yield reductions. Consequently, the N^O_{soil} reservoir will be depleted over time. If uncertainty in the mineralization rate is not considered with scenarios 2 and 3, then yield reduction can be minimized but the risk for N migration below the root zone toward groundwater increases.

Fig. 5 indicates that the potential migration of N below the root zone can be minimized when the N^O_{soil} is low. The majority of the SSC from the DWW was therefore removed as part of the NMP imple-

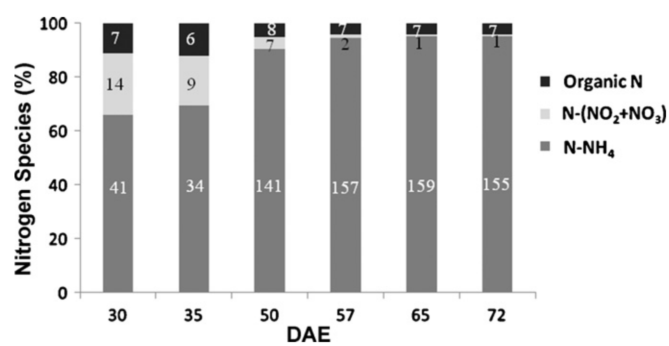

Fig. 6. The percent composition of organic and inorganic N species in dairy wastewater during the wheat-rye 2007 growing season as a function of day after emergence (DAE). The numbers inside the bars denote mg L^{-1} of the indicated N species.

Table 3
Salts and macro-nutrients of a raw and treated dairy wastewater (DWW). Treatment included solid separator, sedimentation tank and sand filter.

Category	Component	Raw DWW	Treated DWW
General	EC (dS m^{-1})	3.7	3.2
	SSC (mg L^{-1})	1611.4	199.1
	pH	7.57	8.16
Salts (mg L^{-1})	Na	182.5	149.9
	Ca	378.3	299.3
	Mg	243.1	231.4
	Cl	174.2	175.8
	S-SO_4	109.1	70.4
	HCO_3	2163.1	1829.0
Macro-nutrients (mg L^{-1})	N-(NH_4 + NO_2 + NO_3)	157.4	145.2
	Organic N	55.5	6.9
	K	404.9	380.5
	Total P	39.0	27.9

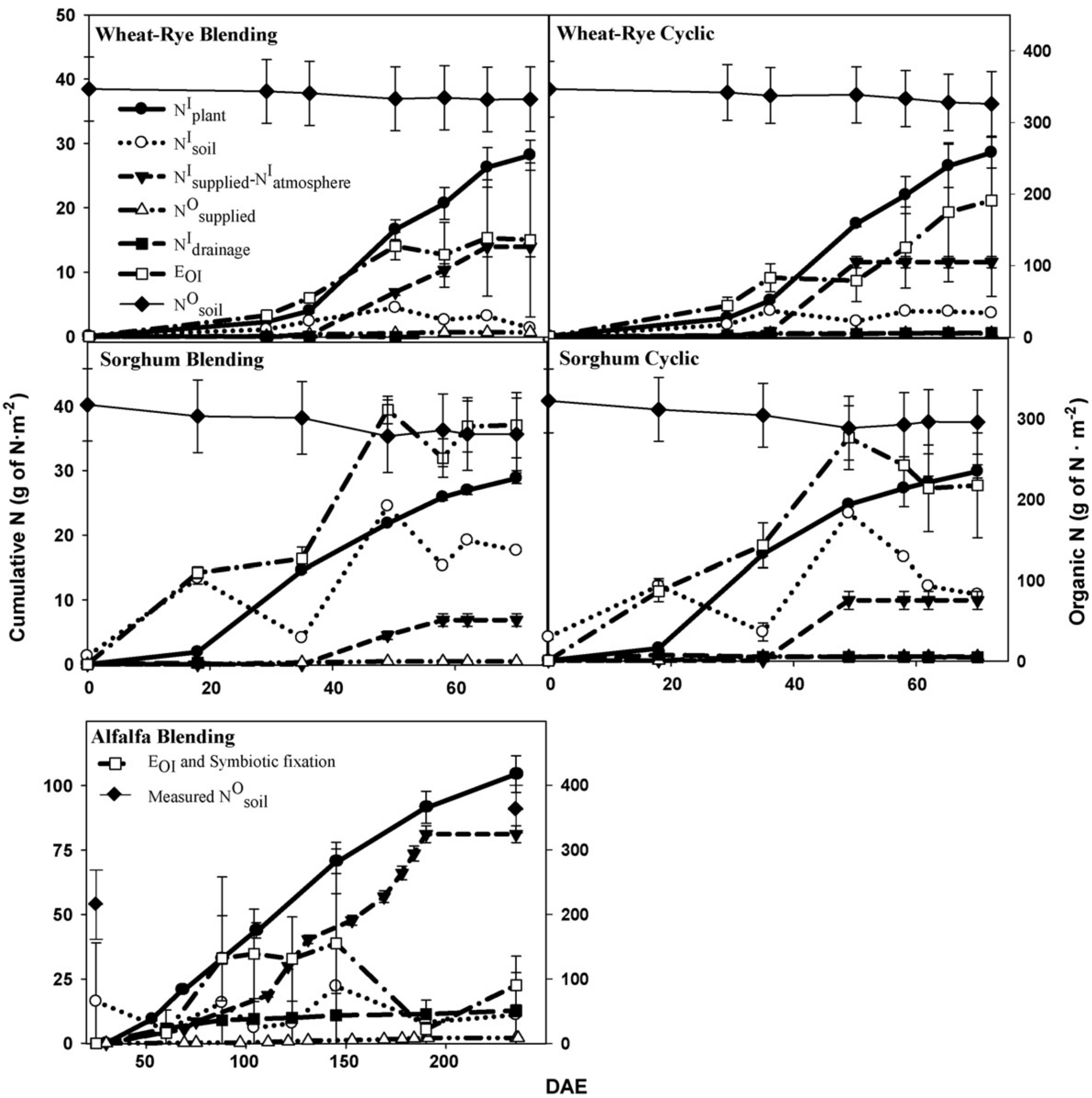

Fig. 7. Soil inorganic and organic N reservoirs (N^I_{soil} and N^O_{soil}) and cumulative values of N uptake by plant (N^I_{plant}), exchange to/from organic and inorganic N forms (E_{OI}), N loss to drainage ($N^I_{drainage}$), supplied organic N ($N^O_{application}$), and supplied inorganic N minus loss to the atmosphere ($N^I_{application} - N^I_{atmosphere}$) in the root zone are presented as a function of day after emergence (DAE). Data is presented as g of N m^{-2} for wheat-rye (30 cm root zone), sorghum (60 cm root zone) and the alfalfa (90 cm root zone). Error bars represent measured or calculated standard deviations. The value of E_{OI} reflects changes due to mineralization for wheat-rye and sorghum, and mineralization and N fixation for alfalfa.

mentation with an inclined screen separator, a sedimentation tank and a sand filter. In addition to this NMP consideration, lower SSC in the DWW allowed us to use a water application system with a high uniformity (micro-sprinkler). The inorganic and organic N species and their distribution in applied DWW during the 2007 winter growing season (wheat-rye) are presented in Fig. 6. The organic N was relatively constant throughout the growing season (6.12–7.78 mg L^{-1}), and the inorganic N fraction increased from 90 to 97% of the total N. Fig. 6 also indicates that N-NH_4 was the dominant N form in the DWW (Campbell-Mathews et al., 2001; Cameron et al., 2002; Wang et al., 2004). Temporal variability in the fraction of N-NH_4 and N-($NO_2 + NO_3$) in the DWW is due to NH_3 volatilization and nitrification during storage (Bussink and Oenema, 1998). The DWW treatment was found to also have an effect on many chemical properties (Table 3). A small reduction in EC was measured and was attributed to adsorption (Rodgers et al., 2005) and removal of suspended solids.

3.3. Plant available N, P, and K

A conservative NMP approach that depletes the N^O_{soil} reservoir over time and minimizes the migration of NO_3^- below the root zone was implemented at our field site for wheat-rye and sorghum during 2007 and is summarized in Fig. 7. Here N^I_{soil}, N^O_{soil} and cumulative values of N^I_{plant}, E_{OI}, $N^I_{drainage}$, $N^I_{application} - N^I_{atmosphere}$ in the root zone are presented over time (no significant difference in the level of $P < 0.05$ were found between cyclic and blending treatments). Initial low N^I_{soil} and minor changes in $N^I_{drainage}$ over time were measure for both cyclic and blending strategies and crops. Average $N^I_{application} - N^I_{atmosphere}$ for the wheat-rye and sorghum crops were 48 and 28% of the total N^I_{plant}, hence the dominant N source was E_{OI} (mineralization). An additional factor influencing $N^I_{application}$ was the low *ET* values during winter. Implementation of the cyclic strategy during these low *ET* conditions could not add sufficient N to match plant requirements for several weeks, without adding DWW in excess of *ET*.

Decreases in N^O_{soil} over time are shown in Fig. 7 for both wheat-rye and sorghum plots. A comparison between measured and calculated (N mass balance) values of N^O_{soil} at the beginning of winter 2008 revealed no significant difference. The final calculated and measured N^O_{soil} reservoir at the beginning of winter 2008 was found to be 267.9 ± 45.1 and 220.2 ± 44.6 g for the blending strategy and 276.6 ± 39.8 and 236.3 ± 38.9 g of organic N m^{-2} for the cyclic strategy.

Average mineralization rates were 1.23E−03 day^{-1} during the wheat-rye growing season and 2.54E−03 day^{-1} during the sorghum growing season. The elevated rates during summer were associated with higher soil temperatures (the average soil temperatures for the winter and summer growing seasons at −15 cm were 15.6 and 24.5 °C, respectively) that accelerated the mineralization process (Watts et al., 2007). These mineralization rates are lower than earlier studies using DWW (Feng et al., 2005; Stenger et al., 2001). This is likely due to the low organic content of the applied DWW that was treated, and the fact that most of the organic N in the soil was plant residuals (low C to N ratio).

The typical concentrations ratio of N, P and K in the applied DWW were 10:1.93:26.2 (Table 3). Direct measurements of P and K contents in plant tissues were not made during the course of the growing season. However, plant uptake rates of N, P, and K by wheat and sorghum have been reported to be 10:1.9:11.5 and 10:1.4:8.75, respectively (Bar-Tal et al., 2004; Vanderlip and Reeves, 1972). If these nutrient uptake ratios are assumed then P and K will be applied in excess and accumulated in the root zone when a NMP based on N is implemented to meet crop demand. Excess application of P becomes an environmental concern when surface water runoff and shallow water tables can mobilize the P into surface water bodies (Wang et al., 2004). Yet, arid and semi-arid environments are mostly associated with deep water tables, a high capacity of mineral soils for P adsorption and limited runoff to nearby surface water due to efficient water application.

Fig. 8 presents concentrations of plant available K and P (phosphorus from phosphate, P-PO_4) in the soil profile at the beginning of the 2007 winter growing season (initial) and the end of the 2007 summer crop season (final) for both blended and cyclic dairy wastewater application strategies. The distributions of K and P exhibited changes primarily in the upper 50 cm of the soil profile, where roots were most active in water and nutrient uptake. The actual deficit $N^I_{application}$ (Fig. 7) corresponded to 5.05 g of P m^{-2}, relative to estimated 8.65 g of P m^{-2} taken up by the crop. Therefore, the final soil P content with both strategies is less than the initial content. However, if $N^I_{application}$ is matched to N^I_{plant} as the main N sink, P will be applied in excess and accumulate in the soil. Similarly, excess amounts of K in the DWW and the large pool of K in the soil profile causes accumulation of K in the root zone for both cyclic and blending strategies.

3.4. Nitrogen fixation—alfalfa 2008

Since no significant differences in cyclic and blended treatments were observed during 2007, only the blended treatment was implemented on alfalfa during 2008. In contrast to wheat-rye hybrid (winter 2007) and sorghum (summer 2007) crops discussed above, alfalfa (summer 2008) is a legume and may also obtain N through

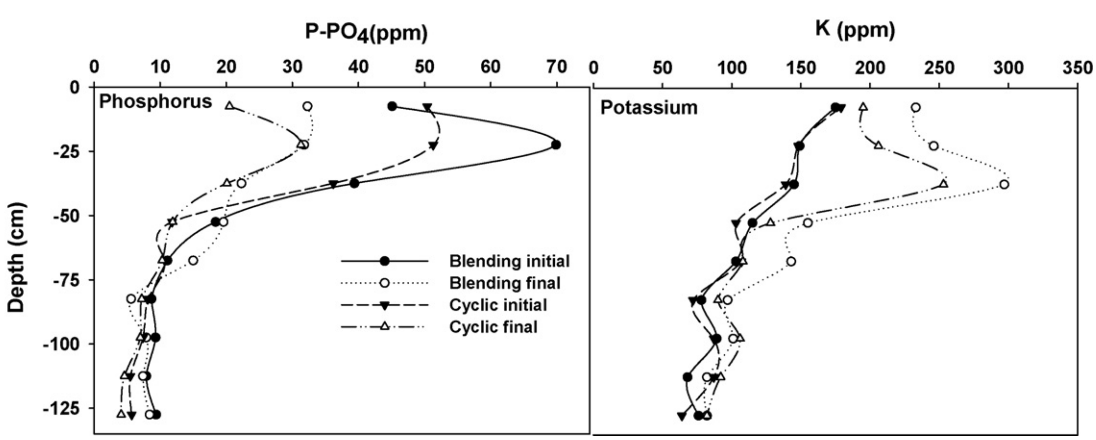

Fig. 8. Plant available phosphorus (P-PO_4) and potassium (K) in the soil profile at the beginning (initial) of the wheat-rye and end (final) of the sorghum growing seasons in 2007 for the blending and cyclic water application strategies.

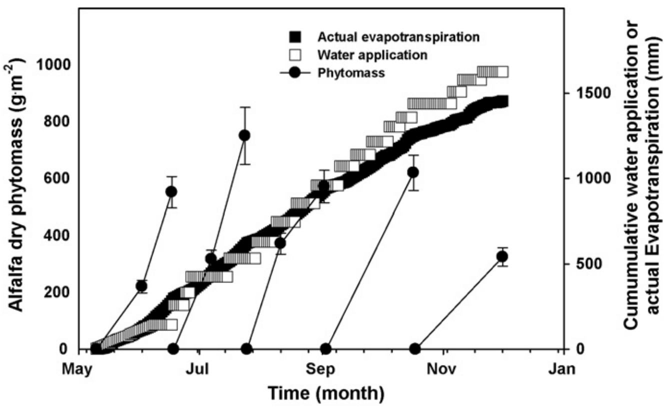

Fig. 9. Dry phytomass, cumulative water application and actual evapotranspiration throughout the five growing cycles of alfalfa in 2008. The error bars reflect the estimated error associated with our sampling procedure for alfalfa (10%).

fixation. The implications of N fixation on efficient NMP implementation will be discussed below.

Similar to wheat-rye hybrid and sorghum data shown in Table 2 and Fig. 2, an efficient water mass balance was implemented for alfalfa during 2008. Dry phytomass, cumulative water application and cumulative ET_{actual} throughout the five growing cycles of alfalfa in 2008 are presented in Fig. 9. The error bars reflect the estimated error associated with our sampling procedure for alfalfa (10%). Dry phytomass ranged between 325 g m^{-2} at the last growing cycle to 750 g m^{-2} at the second growing cycle (ending July 24th). The relatively slow growth rates during the last cycle was due to seasonal variations in climate; i.e., the average maximum and minimum air temperatures and solar radiation during this period were relatively low with values of 23.1, 3.07 °C and 265.3 W m^{-2}, respectively. In contrast, the low dry phytomass of the first cycle was related to the extensive weed growth that interfered with the normal development of the alfalfa during this period. The ratio between the total water applications (1626.7 mm) to the total ET_{actual} (1455.5 mm) corresponded to a leaching fraction of 11.7%. The calculated crop coefficients, K_c, were consistent with published data (Allen et al., 1998) and varied between 0.4 after harvesting to 1.2 when full foliage cover was reached. Similar to 2007 data shown in Fig. 2, changes in $|h|$ were restricted only to the upper 60 cm of the soil profile due to the accurate water balance.

The alfalfa 2008 growing season started after a long fallow period (November 2007–April 2008). A total of 25.7 cm of rainfall occurred during the fallow period that leached salts further into the soil profile. Similar to the 2007 data presented in Fig. 3, the TDS increased over the growing season. The TDS in the soil profile (0 to −170 cm) at the beginning of the growing season (May 2008) was 937.7 ± 338 g m^{-2} and at the end (December 2008) was 1391.7 ± 265 g m^{-2}. This increase was pronounced at all depths and especially the upper 30 cm (98.8 g m^{-2} versus 254.3 g m^{-2}).

Fig. 7 shows the various components of the N balance that were measured for alfalfa during 2008. Since alfalfa can fix atmospheric N through nodules, the value of E_{OI} now accounts for the net exchange between organic and inorganic N forms due to both mineralization and atmospheric N fixation. Due to this additional complication, only initial and final values of measured N^{O}_{soil} are shown in Fig. 7 for alfalfa. Recall that a very conservative NMP approach was implemented for wheat-rye and sorghum crops in 2007 that depleted the soil organic N. In contrast, a less conservative NMP strategy was implemented for alfalfa during 2008 due to a greater value of N^{I}_{plant}, a deeper root system, and the desire to suppress atmospheric N fixation. Specifically, the cumulative value of N^{I}_{plant} was 104 g of N m^{-2} for alfalfa in comparison to 60 g of N m^{-2} for both wheat-rye hybrid and sorghum. The depth of the root zone, where roots are most active in water and nutrient uptake under irrigated conditions, for alfalfa was approximately 90 cm in comparison to 30 and 60 cm for wheat-rye hybrid and sorghum, respectively. A larger root zone allows nutrients to be extracted over a larger area and to implement a more flexible schedule for lagoon water application. In addition, by maintaining a high N concentration in the root zone, we can minimize the needs of the plant to seek for alternative N sources and theoretically apply more DWW. The value of $N^{I}_{application} - N^{I}_{atmosphere}$ for the alfalfa was selected to be 76% of the total N^{I}_{plant}. This implies that the remaining 24% of N^{I}_{plant} comes from mineralization or atmospheric N fixation.

Several implications for the less conservative NMP strategy that was implemented on alfalfa during 2008 are discussed below. First, an increase in measured N^{O}_{soil} is shown in Fig. 7 for alfalfa. This observation can be attributed to three factors, namely: (i) intensive root growth of the alfalfa that increased the total N^{O}_{soil}, (ii) the less conservative NMP approach yielded a higher ratio of $N^{I}_{application} - N^{I}_{atmosphere}$ to the total N^{I}_{plant}, and (iii) the mechanism of N fixation through nodules reduced the need of mineralized N^{O}_{soil}, and induced immobilization of inorganic N. Amounts of N in excess of plant uptake requirements were apparently generated due to these factors. Consequently, 15% of the supplied inorganic N was measured to be steadily drained below the root zone throughout the growing season under the applied leaching factor of 11.7%. This observation indicates that accurate implementation of NMPs for crops that fix nitrogen will be problematic, and that there is a potential risk of groundwater contamination by mobile nitrogen species (i.e., nitrate). One potential solution to these NMP difficulties is to alternate between legumes (alfalfa) and cereals (wheat-rye hybrid and sorghum).

4. Conclusions

A NMP was implemented in a semi-arid environment on a wheat-rye hybrid and sorghum rotation during 2007 and on alfalfa during 2008, where salts and N were assumed to be the primary environmental concerns. Cyclic and blending DWW application strategies, varying in nutrient application timing, were investigated during 2007. Only minor differences were found between these two strategies, therefore the key findings discussed below were valid for both conditions.

- NMPs need to account for the soil organic N reservoir in the N mass balance. This may induce difficulties in conservative NMP implementation that is protective of the environment due to: (i) difficulties in estimation of mineralization rates and its spatial variability, (ii) delayed availability of the organic N for plant uptake, and (iii) continuous mineralization and potential nutrient leaching during fallow periods.
- NMPs should be designed to deplete the soil organic reservoir, and to accurately apply plant available inorganic N at rates that minimize the migration of nutrients below the root zone (i.e., to meet *ET*). This was achieved by using DWW that was treated to remove most of the SSC, and applying only a fraction of the plant N uptake with DWW.
- Use of leguminous crops that fix atmospheric N, such as alfalfa, adds challenges to implementation of environmentally protective NMPs because this nutrient source is difficult to quantify.
- NMPs that precisely apply water and DWW to meet *ET* will accumulate salts in the root zone that may restrict plant growth, and water and nutrient uptake. If this reduction in *ET* is not considered at NMP sites, additional leaching and contaminant migration will occur. This point is strongly dependent on the salt tolerance

of the crop, suggesting that NMPs should use only salt tolerant crops.

- The leaching timing of excess salts below the root zone is a crucial aspect in NMP design because of continuous mineralization of organic N during fallow periods. In order to minimize NO_3^- leaching, pre-irrigations should be scheduled at the end of the growing season, when the soil profile is depleted from NO_3^- by plant uptake.
- A comprehensive measurement of N mass balance in the root zone requires information on losses to the atmosphere during irrigation. Atmospheric losses may be minimized by applying DWW during times that are associated with low potential *ET* (i.e., early morning), or through drip systems that minimize the exposure of DWW to the atmosphere.
- Differences in the concentrations ratio of N, P, and K between DWW and plant uptake may lead to accumulation of P and K in the root zone.

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